

SUPERNOVA FEEDBACK KEEPS GALAXIES SIMPLE

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ABSTRACT

Galaxies evolve continuously under the influence of self-gravity, rotation, accretion, mergers and feedback. The currently favored cold dark matter cosmological framework, suggests a hierarchical process of galaxy formation, wherein the present properties of galaxies are decided by their individual histories of being assembled from smaller pieces. However, recent studies have uncovered surprising correlations among the properties of galaxies, to the extent of forming a one-parameter set lying on a single fundamental line. It has been argued in the literature that such simplicity is hard to explain within the paradigm of hierarchical galaxy mergers. One of the puzzling results, is the simple linear correlation between the neutral hydrogen mass and the surface area, implying that widely different galaxies share very similar neutral hydrogen surface densities. In this work we show that self-regulated star formation, driven by the competition between gravitational instabilities and mechanical feedback from supernovae, can explain the nearly constant neutral hydrogen surface density across galaxies. We therefore recover the simple scaling relation observed between the neutral hydrogen mass and surface area. This result furthers our understanding of the surprising simplicity in the observed properties of diverse galaxies.

Subject headings: galaxies: kinematics and dynamics — galaxies: ISM — supernova remnants — galaxies: stellar content

1. INTRODUCTION

In a hierarchical process of galaxy formation (Cole et al. 2000), within the currently favored Λ -CDM cosmological framework, the present properties of galaxies are decided by their individual histories of being assembled from smaller halos (Lacey & Cole 1993). Moreover, these galaxies evolve continuously under the influence of self-gravity, rotation, accretion and feedback. However, Disney et al. (2008) have recently reported surprising correlations among the properties of galaxies, to the extent of forming a one-parameter set lying on a single fundamental line (Garcia-Appadoo et al. 2009). van den Bergh (2008) has argued that such simplicity is hard to explain within the paradigm of hierarchical galaxy mergers. One of the puzzling results (Giovanelli & Haynes 1983; Haynes & Giovanelli 1984; Verheijen & Sancisi 2001; Rosenberg & Schneider 2003; Garcia-Appadoo et al. 2009), is that the neutral hydrogen mass across these galaxies scales almost linearly with surface area, implying that widely different galaxies share very similar neutral hydrogen surface densities. This nearly constant HI surface density has been pointed out in literature to be an intriguing puzzle, demanding an explanation.

In this work we argue that correlation between the neutral hydrogen mass and surface area may be preserved, despite the complex merger histories of the galaxies, by self-regulated star formation, driven by the competition between gravitational instabilities in the rotating disk and mechanical feedback from supernovae. When mergers drive a galaxy away from the fundamental line, self regulation of the porosity of the ISM and gravitational instability of the star forming disk, as proposed by Silk

(1997), can bring the neutral hydrogen surface density back to the value which is predicted in our simple model. This can explain the regulation of the neutral hydrogen surface density in galaxies, explaining part of the surprising simplicity in the observed properties of galaxies.

2. SURFACE DENSITY OF GAS IN GALAXIES

Evidence of a nearly universal neutral hydrogen (HI) surface density in galaxies has been accumulating over the past three decades. The initial hints came from single-dish 21 cm radio observations of nearby galaxies. Giovanelli & Haynes (1983) reported neutral hydrogen (HI) observations of 24 galaxies in the Virgo cluster, using the Arecibo telescope. The HI sizes and masses were found to be correlated in the same manner, irrespective of whether they were HI rich or HI poor. A similar correlation was soon found between the optical sizes and HI masses of 288 isolated galaxies (Haynes & Giovanelli 1984). It was also found that the optical diameters of spiral disk are better correlated with the HI mass than the morphological type (Haynes & Giovanelli 1984). A deeper survey by Verheijen & Sancisi (2001) has revealed similar correlations for galaxies in the Ursa Major Cluster. The Arecibo Dual-Beam Survey (Rosenberg & Schneider 2000) (ADBS) has found HI in 265 galaxies in a “blind” survey of $\sim 430\text{deg}^2$ of sky. While most of the ADBS galaxies were unresolved at the resolution of the Arecibo, the Very Large Array (VLA) was used for interferometric mapping of 84 galaxies and determine accurate sizes of 50 of them. A comparison of HI masses and HI sizes of these along with 53 galaxies with high resolution maps from literature revealed that they were consistent with a nearly constant average HI surface density of the order $\sim 10^7 M_\odot \text{ kpc}^{-2}$ (Rosenberg & Schneider 2003). The HI masses of indi-

vidual ADBS galaxies, spanning 3 orders of magnitude, deviate by only ~ 0.13 dex (1σ) from those expected from a constant HI surface density. This puts the evidence, for a regulated HI surface density across galaxies, on a firm observational basis.

A recent study of HI selected galaxies (free from optical selection effects) found using the Parkes radio telescope and identified with SDSS sources, has shown that 6 observed parameters, namely the dynamical mass (M_d), HI mass (M_{HI}), luminosity, color, and two radii containing 50% and 90% of the observed luminosity, have 5 independent correlations among themselves (Disney et al. 2008). This implies that the galaxies form a single parameter family and are not removed significantly from their fundamental line by the diverse merger histories that they would have had in the process of hierarchical galaxy formation. Some of the correlations have already been widely known and discussed in other forms, such as the correlation (Gavazzi et al. 1996) between luminosity and dynamical mass. Disney et al. (2008); Garcia-Appadoo et al. (2009) report a tight linear correlation in the already established relation between the HI mass and the surface area. The nearly constant HI surface density is argued in literature to be an intriguing puzzle which demands an explanation (Garcia-Appadoo et al. 2009). We discuss below, a physically motivated explanation for this important observation.

3. GRAVITATIONAL INSTABILITY IN DISK GALAXIES

Below a surface density threshold, azimuthally integrated star formation in giant HII regions across a galaxy ceases (Kennicutt 1989). The existence of this threshold is traditionally stated in the form of the Toomre parameter for gravitational instability (Spitzer 1968). Below a Toomre parameter $Q \lesssim 1$, rotation support and gas pressure cannot stabilize a thin self-gravitating disk against gravitational instability Safronov (1960); Toomre (1964). Here Q is defined as

$$Q \equiv \mu_{cr}/\mu_{gas}, \quad (1)$$

where the critical gas surface density is given by $\mu_{cr} \equiv \Omega_g/\pi G$, in terms of the angular velocity Ω and velocity dispersion σ_g in the gas disk. Schaye (2004) has demonstrated that results from detailed considerations including not only self-gravity, but metals, dust and UV radiation, coincide with this empirically derived surface density threshold for star formation.

This condition depends on the local angular velocity, which we may define the as $\mathbf{\Omega} = \nabla \times \mathbf{V}$. Using cylindrical polar coordinates we can now write down the curl operator as

$$\begin{aligned} \nabla \times \mathbf{A} = & \left(\frac{1}{\rho} \frac{\partial A_z}{\partial \phi} - \frac{\partial A_\phi}{\partial z} \right) \hat{\rho} + \left(\frac{\partial A_\rho}{\partial z} - \frac{\partial A_z}{\partial \rho} \right) \hat{\phi} \\ & + \frac{1}{\rho} \left(\frac{\partial (\rho A_\phi)}{\partial \rho} - \frac{\partial A_\rho}{\partial \phi} \right) \hat{z}. \end{aligned} \quad (2)$$

Assuming, rotation and translation symmetry along $\hat{\phi}$ and \hat{z} respectively, if the bulk motion of the gas is only in the $\hat{\phi}$ direction (as would be the case if the motion is purely Keplerian) we may write down the angular veloc-

ity as

$$\Omega = |\mathbf{\Omega}| = |\nabla \times \mathbf{V}| = \left| \frac{1}{r} \left(\frac{\partial (rV(r))}{\partial r} \right) \hat{z} \right|, \quad (3)$$

where the radial coordinate ρ has been replaced by r , to avoid confusion with density. In nearly rigid rotors such as dwarf galaxies, the velocity is given by $V(r) = \Omega_0 r$. In such a case, $|\nabla \times \mathbf{V}|$ is given by $2\Omega_0$ (Arfken & Weber 2005, problem 2.4.7). For flat ($V(r) = V_0$) rotation curves $|\nabla \times \mathbf{V}| = V_0/r$. Hence, for all these cases, at boundary of the starforming disk, the local value of the angular velocity is comparable to the global value. Hence, following Silk (1997) we shall use the global angular velocity of the disk in the rest of this work.

The global angular velocity can now be expressed as

$$\Omega_0 = \sqrt{\frac{GM_d}{R^3}} \quad (4)$$

in terms of the enclosed dynamical mass within the gas disk. Replacing $M_d = 4\pi\rho_d R^3/3$, where ρ_d is the nearly universal dynamical mass density (Disney et al. 2008; Garcia-Appadoo et al. 2009), we have $\Omega_0 = \sqrt{4\pi G\rho_d/3}$. Substituting, we get

$$\mu_{cr} = \frac{\sigma_g}{\pi} \sqrt{\frac{4\pi\rho_d}{3G}}. \quad (5)$$

Now, we note that for the star forming disk to be long lived, it may only be marginally unstable. Q is seen to be ~ 1 throughout the star forming regions in well observed disk galaxies (Kennicutt 1989). This implies that throughout the star forming disk the mean gas surface density is of order $\mu_{gas} \sim \mu_{cr}$. Hence, the mean surface density of gas is controlled primarily by the dynamical mass density ρ_d and the gas velocity dispersion σ_g .

One of the tight correlations seen by Disney et al. (2008); Garcia-Appadoo et al. (2009) is between the dynamical mass and cube of the optical radius, implying a roughly constant average dynamical mass density (within the radii of their star forming disks) for galaxies. It is expected that Dark Matter contributes most of the gravitational mass of the galaxies, hence a physical explanation of this observation would require an understanding of the nature of Dark Matter. Whether or not hierarchical halo build-up within a Λ -CDM cosmology can explain this observation is still under investigation. Loeb & Weiner (2010) have suggested that cold dark matter particles interacting through a Yukawa potential could make halos beyond a certain critical density evaporate over an Hubble time. This may set a characteristic scale to the peak density of dark matter halos. Note however that the dark matter halos of galaxies are much larger than the sizes of their star forming disks. As a result, most of the dark matter may lie further out. Kent (1987) points out that the relative contributions of the dark matter halo and stellar contents to the dynamical mass of a galaxy vary significantly with its luminosity and morphological type. In the rest of this work, we shall use the simple $M_d \propto R^3$ relation observed by Disney et al. (2008); Garcia-Appadoo et al. (2009), showing a shared $\rho_d \sim 10^7 M_\odot kpc^{-3}$ across galaxies. This implies, that the mean surface density is controlled essentially by the gas velocity dispersion σ_g which is driven by energy input from supernova explosions in the disk.

4. MECHANICAL FEEDBACK FROM SUPERNOVAE

The distribution of gas in our galaxy has been variously described in the past as being similar to that of Swiss Cheese (Cox & Smith 1974), as a Cosmic Bubble Bath (Brand & Zealey 1975) or as the Violent Interstellar Medium (McCray & Snow 1979). The basic idea is that supernova remnants are full of coronal gas which can persist for long enough, as it radiates very inefficiently by bremsstrahlung, so that a modest supernova rate may produce an interconnected morphology of hot gas. Shells and supershells (Heiles 1979) have been found in the neutral hydrogen distribution of galaxies. McCray & Kafatos (1987) suggested that stellar winds and repeated supernovae from an OB association may create cavities of coronal gas in the interstellar medium leading to the formation of supershells. Chakraborti & Ray (2011) have demonstrated that this mechanism can explain the dynamics of a HI supershell found in M101 driven by mechanical energy input from supernovae in a giant young stellar association.

The fraction of volume filled by supernova-driven hot gas is referred to as the porosity (P) of the interstellar matter (ISM). The porosity is driven by the supply of hot gas from supernova remnants (SNRs) and is related to the 4-volume of a SNR in the cooling phase (Cioffi et al. 1988) (ν_{SN}) and the supernova rate per unit volume (r_{SN}) as

$$P = \nu_{SN} \times r_{SN}. \quad (6)$$

The supernova rate is related to the recent star formation rate per unit volume (ρ_*) as

$$r_{SN} = \rho_*/m_{SN}, \quad (7)$$

where m_{SN} is the total mass of star formation required on an average to produce each core collapse supernova. Silk (1997) has argued that if P is too high, it would suppress the efficiency of star formation. Since the supernova rate follows the recent star formation rate, the situation called “blowout” would throttle the supply of hot gas and bring down the value of P . On the other hand if P was too low, it would allow the cold gas phase to dominate and form new stars more efficiently, some of which would soon explode as supernovae and drive up the value of P . Hence, there would be a self regulation process that would control P .

In this manner, Silk (1997) shows that supernova explosions supply the energy input necessary to maintain the velocity dispersion in the gas phase at

$$\sigma_g = 6.90 P^{-0.58} n_g^{0.1} E_{51}^{0.2} \zeta^{0.008} \text{km s}^{-1}. \quad (8)$$

This expression depends only weakly on the gas density n_g , energy input from individual supernovae $E_{51} \times 10^{51}$ ergs, and the metallicity ζ all of which have typical values of order unity. The dependence on these parameters is dropped from our subsequent equations. Assuming self-regulated star formation ($P \sim 0.5$) the predicted gas velocity dispersion has been shown (Silk 1997) to be $\sigma_g \sim 11 \text{ km s}^{-1}$, close to the value of observed by Stark & Brand (1989) for the three-dimensional peculiar velocity dispersion of interstellar molecular clouds within 3 kpc of the Sun.

Joung et al. (2009) have studied the effect of the supernova rate on the interstellar turbulent pressure and

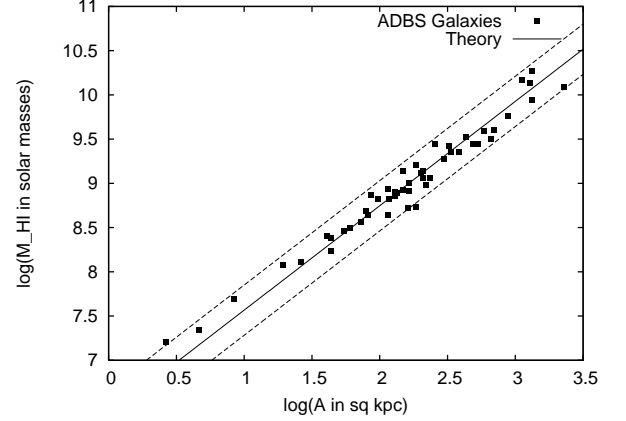


FIG. 1.— **Surface area and HI masses:** ADBS galaxies (Rosenberg & Schneider 2003) are plotted as black squares. The solid line is the theoretical curve (Equation 16) from this work and the area between the dashed lines represents the 2σ variance region. Note the simple relation in which the HI mass scales almost linearly with the surface area, implying a regulated HI surface density across galaxies. This hitherto unexplained feature is reproduced by our simple model.

confirmed a very weak dependence of σ_g on the star formation rate. They find simulated HI emission lines widths of $10 - 18 \text{ km s}^{-1}$ for models with SN rates that range from 1 to 512 times the Galactic SN rate. Hence, the characteristic values for ρ_d and σ_g when plugged into Equation 5, set the characteristic scale for the gas surface density to a ballpark figure of $\sim 10^7 M_\odot \text{ kpc}^{-2}$, which is close the observed value (Rosenberg & Schneider 2003) for the ADBS galaxies.

5. REGULATED SURFACE GAS DENSITY

Integrating the star formation rate per unit volume over an entire galaxy Silk (1997) provides the total SFR as

$$\dot{M}_* \simeq 2.6 \times v_{rot,200}^{5/2} Q^{-3/2} \left(\frac{P}{0.5} \right)^{-0.87} M_\odot \text{ yr}^{-1}, \quad (9)$$

where $v_{rot,200}$ is the maximum rotational velocity of the galaxy, normalized to 200 km s^{-1} . The exact expression (Silk 1997) depends on well understood quantities like the total mass of stars formed to yield one core collapse supernova, the mechanical energy output of an average supernova, and depends only weakly on the metallicity. As the disk becomes gravitationally unstable if Q decreases, the SFR increases and the resulting supernovae increase the porosity P . This reduces the supply of cold gas and hence suppresses the star formation rate. Hence Silk (1997) points out that this expression provides an explicit demonstration of disk self-regulation and self-regulated star formation ensures $P \sim 0.5$ and $Q \sim 1$. We use these values in the rest of this work.

Using the definition of the dynamical mass ($M_d = (\Delta V)^2 R_{90\%}/G$) from Kulkarni & Heiles (1988), we can express $v_{rot,200}$ as

$$v_{rot,200} \simeq 1.04 \times \sqrt{\frac{M_{d,11}}{R_{10}}}, \quad (10)$$

where $M_{d,11}$ is the dynamical mass normalized to $10^{11} M_\odot$ and R_{10} is the 90% optical containment radius ($R_{90\%}$) normalized to 10 kpc. The dynamical mass has

been found to be correlated with the cube of the optical radius (Garcia-Appadoo et al. 2009). The implied roughly constant global dynamical density is of the order of $\rho_d \sim 10^7 M_\odot \text{kpc}^{-3}$. Exploiting this observed relation we have

$$M_{d,11} \simeq 0.42 \rho_7 R_{10}^3, \quad (11)$$

where $\rho_7 = \rho_d / 10^7 M_\odot \text{kpc}^{-3}$. Substituting for $v_{\text{rot},200}$ and then for $M_{d,11}$, we get

$$\dot{M}_* \simeq 0.95 \times \rho_7^{\frac{5}{4}} R_{10}^{\frac{5}{2}} M_\odot \text{yr}^{-1}. \quad (12)$$

One may interpret the Gavazzi et al. (1996) relation between total luminosity (a proxy for the stellar mass) and dynamical mass (proportional to R^3 because of the shared ρ_d) as $M_* \propto R^3$. This implies that the doubling time for the stellar mass, scales as

$$\tau = \frac{M_*}{\dot{M}_*} \propto R^{\frac{1}{2}}. \quad (13)$$

Objects with larger doubling times have older stellar populations on an average. This may explain why bigger galaxies are systematically redder.

This star formation rate allows us to estimate the mean SFR per unit area as

$$\Sigma_{\text{SFR}} \simeq 3.0 \times 10^{-3} \times \rho_7^{1.25} R_{10}^{0.5} M_\odot \text{yr}^{-1} \text{kpc}^{-2}. \quad (14)$$

However Σ_{SFR} is related to the surface density of gas Σ_{gas} by the Kennicutt-Schmidt Law Kennicutt (1998) as

$$\Sigma_{\text{SFR}} = (2.5 \pm 0.7) \times 10^{-4} \times \left(\frac{\Sigma_{\text{gas}}}{1 M_\odot \text{pc}^{-2}} \right)^{1.4 \pm 0.15} M_\odot \text{yr}^{-1} \text{kpc}^{-2}. \quad (15)$$

If the molecular gas fraction is $\ll 1$, which is true for most disk galaxies, the mean surface density of HI Σ_{HI} is comparable to the total gas surface density Σ_{gas} . This assumption will make a proportional error comparable to the molecular gas fraction. Hence assuming $\Sigma_{\text{HI}} \sim \Sigma_{\text{gas}}$, eliminating the Σ_{SFR} and integrating over the surface area, we obtain the relation between the gas mass and the surface area as

$$\log\left(\frac{M_{\text{HI}}}{1 M_\odot}\right) \simeq (6.91 \pm 0.08) + 1.18 \times \log\left(\frac{A}{1 \text{kpc}^2}\right) + 0.89 \times \log\left(\frac{\rho_d}{10^7 M_\odot \text{kpc}^{-3}}\right), \quad (16)$$

where $A \equiv \pi R^2$ is the cross sectional surface area presented by the galaxy. Given that dynamical mass density (ρ_d) is not seen to vary much across galaxies, the almost linear relation between the total HI mass and the surface area implies very similar HI surface densities across a range of galaxies. The normalization matches the observed (Rosenberg & Schneider 2003) relation for $\rho_7 = 0.26$ which lies within the range of its observed (Garcia-Appadoo et al. 2009) values. The HI masses, of ADBS galaxies (Rosenberg & Schneider 2003), spanning 3 orders of magnitude, vary only by ~ 0.14 dex (1σ) from the theoretical curve. However, this scatter is larger than the scatter propagated from the Kennicutt-Schmidt Law (Kennicutt 1998). The excess scatter may be attributed to the scatter in core properties of halos such as ρ_7 . It has been pointed out by Loeb & Weiner (2010) that numerical simulations are required to determine the scatter in dark matter core densities as a function of mass

and redshift. This would be important for dark matter dominated halos. Gavazzi et al. (1996) show a correlation between total luminosity and the dynamical mass. If most of the dynamical mass is provided by the stellar content, it would be important to study the scatter in this relationship.

6. DISCUSSIONS

Our result shows that the present understanding of mechanical feedback from supernovae, leading to self regulated star formation (Silk 1997), can account for the regulation of HI surface density across galaxies to a characteristic value of around $\sim 10^7 M_\odot \text{kpc}^{-2}$ (Rosenberg & Schneider 2003). The predicted HI surface density depends on the mean density of the dynamical mass, which is likely to be provided by a combination of dark matter and stellar content. As to why galaxies are observed (Garcia-Appadoo et al. 2009) to share similar dynamical mass densities is still an open case requiring further investigation. Cold dark matter particles interacting through a Yukawa potential (Loeb & Weiner 2010) could provide a natural explanation for a characteristic density in dark matter dominated halos. The correlation (Gavazzi et al. 1996) between luminosity and dynamical mass may be important in halos dominated by the stellar content.

The model of self regulated star formation (Silk 1997) has been shown in this work to provide a scaling between doubling time and radius. This could explain why larger galaxies are systematically redder. This relation should be used in conjunction with population synthesis models such as Starburst99 (Leitherer et al. 1999) to predict colors as a function of galaxy size. This could provide an interesting test of this model in future.

Even if mergers drive a galaxy away from the fundamental line, self regulation of the porosity of the ISM and Toomre parameter of the star forming disk can bring the HI surface density back to the value which is predicted in our simple model and observed in a wide range of galaxies. In a framework for hierarchical galaxy mergers this can happen multiple times in a galaxy's history, until it eventually runs out of neutral hydrogen. A detailed understanding of the proposed mechanism would require self consistent galaxy simulations taking into account the supply of hot gas into the ISM from individual supernovae.

Our model relates the total neutral hydrogen mass of the galaxy with its projected surface area. However in practice, the quantities observed with radio telescopes are the redshift, integrated HI line fluxes and the solid angles on the sky. Fluxes and solid angles behave differently in different cosmological scenarios, as they scale with the luminosity distance d_L and angular diameter distance d_A respectively. This could facilitate their use in testing the Etherington (1933) relation, $d_L = (1+z)^2 d_A$, when future telescopes such as the Square Kilometer Array start to detect red-shifted HI from very distant galaxies.

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REFERENCES

- Arfken, G. B., & Weber, H. J. 2005, *Mathematical methods for physicists* 6th ed.
- Brand, P. W. J. L., & Zealey, W. J. 1975, *A&A*, 38, 363
- Chakraborti, S., & Ray, A. 2011, *ApJ*, 728, 24
- Cioffi, D. F., McKee, C. F., & Bertschinger, E. 1988, *ApJ*, 334, 252
- Cole, S., Lacey, C. G., Baugh, C. M., & Frenk, C. S. 2000, *MNRAS*, 319, 168
- Cox, D. P., & Smith, B. W. 1974, *ApJ*, 189, L105
- Disney, M. J., Romano, J. D., Garcia-Appadoo, D. A., West, A. A., Dalcanton, J. J., & Cortese, L. 2008, *Nature*, 455, 1082
- Etherington, I. M. H. 1933, *Philosophical Magazine*, 15, 761
- Garcia-Appadoo, D. A., West, A. A., Dalcanton, J. J., Cortese, L., & Disney, M. J. 2009, *MNRAS*, 394, 340
- Gavazzi, G., Pierini, D., & Boselli, A. 1996, *A&A*, 312, 397
- Giovanelli, R., & Haynes, M. P. 1983, *AJ*, 88, 881
- Haynes, M. P., & Giovanelli, R. 1984, *AJ*, 89, 758
- Heiles, C. 1979, *ApJ*, 229, 533
- Joung, M. R., Mac Low, M., & Bryan, G. L. 2009, *ApJ*, 704, 137
- Kennicutt, Jr., R. C. 1989, *ApJ*, 344, 685
- . 1998, *ARA&A*, 36, 189
- Kent, S. M. 1987, *AJ*, 93, 816
- Kulkarni, S. R., & Heiles, C. 1988, *Neutral hydrogen and the diffuse interstellar medium*, ed. Kellermann, K. I. & Verschuur, G. L., 95–153
- Lacey, C., & Cole, S. 1993, *MNRAS*, 262, 627
- Leitherer, C., et al. 1999, *ApJS*, 123, 3
- Loeb, A., & Weiner, N. 2010, *arXiv:astro-ph/1011.6374*
- McCray, R., & Kafatos, M. 1987, *ApJ*, 317, 190
- McCray, R., & Snow, Jr., T. P. 1979, *ARA&A*, 17, 213
- Rosenberg, J. L., & Schneider, S. E. 2000, *ApJS*, 130, 177
- . 2003, *ApJ*, 585, 256
- Safronov, V. S. 1960, *Annales d’Astrophysique*, 23, 979
- Schaye, J. 2004, *ApJ*, 609, 667
- Silk, J. 1997, *ApJ*, 481, 703
- Spitzer, L. 1968, *Diffuse matter in space*, ed. Spitzer, L.
- Stark, A. A., & Brand, J. 1989, *ApJ*, 339, 763
- Toomre, A. 1964, *ApJ*, 139, 1217
- van den Bergh, S. 2008, *Nature*, 455, 1049
- Verheijen, M. A. W., & Sancisi, R. 2001, *A&A*, 370, 765